Assimilation Ionosphere Model

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LONG-TERM GOALS

Our main long-term goal is to develop an Assimilation Ionosphere Model (AIM) that provides reliable ionospheric specifications and forecasts. A secondary goal is to use the model to elucidate the physics associated with the creation, transport and decay of plasma density structures and to determine their effects on naval systems.

OBJECTIVES

Our main objective is to construct a physics-based, global, ionospheric specification-forecast model that is capable of ingesting a diverse set of real-time (or near real-time) measurements. The data to be assimilated include slant path TEC's from several Global Positioning System (GPS) satellites, high-quality TEC's from selected satellites with radio beacons, in situ plasma parameters from the SSIES instrument package on the DMSP satellites, digisonde data from selected ground-based stations, and both line-of-sight UV emissions and deduced plasma parameters from the Naval Research Laboratory's SSUSI and SSULI instruments. After AIM is constructed, a secondary objective is to use the model to study the sensitivity of the ionosphere to a wide range of external forcing functions. Of particular interest is the determination of the conditions leading to the creation of plasma density structures and irregularities.

APPROACH

Our approach to developing a reliable ionospheric specification-forecast model is to use a physics-based, global, ionosphere model as the basis for data assimilation. First, the physics-based model will be run for the geophysical conditions that pertain to the desired specification (year, day, time, $F_{10.7}$, Kp, Dst). The result will be a global electron density distribution. This simulated distribution will then be probed the same way instruments probe the real ionosphere and the simulated and measured instrument responses will be compared. The inputs to the global ionosphere model will be adjusted and the model rerun until the simulated and measured parameters agree at the locations and times that the data are available. Some of the algorithms needed for the construction of AIM are already available, but most must be developed. The specific tasks to be accomplished are as follows: (1) Construct an equatorial ionospheric model and couple it to our mid-high latitude model: (2) Develop data quality assessment algorithms for the different data types that we will consider for assimilation; (3) Develop software to simulate the data types that are currently not available; (4) Develop data assimilation algorithms and data quality flags; (5) Construct an executive system to control the running

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14. ABSTRACT
Our main long-term goal is to develop an Assimilation Ionosphere Model (AIM) that provides reliable ionospheric specifications and forecasts. A secondary goal is to use the model to elucidate the physics associated with the creation, transport and decay of plasma density structures and to determine their effects on naval systems.

15. SUBJECT TERMS

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of the model and the data assimilation algorithms; and (6) Conduct a validation of the final AIM product, including assimilation, scientific, and applications validations.

R. W. Schunk has overall responsibility for the project. He is also developing the equatorial ionosphere model and is participating in the construction of the data assimilation algorithms. J. J. Sojka is the main person responsible for the data assimilation and data quality assessment algorithms. V. Eccles is responsible for the model's spatial grid system and for construction of software to simulate the data that are currently not available. L. Zhu is participating both in the construction of the equatorial ionospheric model and the data assimilation work.

WORK COMPLETED

Prior to the reporting period, the numerical coding for the Ionosphere-Plasmasphere Model (IPM) was completed. The model was based on a numerical solution of the coupled continuity and momentum equations for the relevant ions and electrons. Before the numerical solution, the transport equations were first expressed in dipolar coordinates (p,q) and then an additional transformation was made to an x = sinh (q) coordinate for numerical efficiency and stability. At that point, the model took account of four ion species (NO^+, $O2^+$, $N2^+$, O^+) in the E region, O^+ in the F-region, and H^+ in the plasmasphere. The model covers the altitude range from 90 km to geosynchronous altitudes (30,000 km). In addition, prior to the reporting period, the model was improved by taking account of the magnetic field description provided by the International Geomagnetic Reference Field (IGRF) and a new empirical model for the ion and electron temperatures was also added (Titheridge, 1998). These additions were important for properly modeling the equatorial ionosphere at sunset, when spread F irregularities occur, and at night.

During the reporting period, the IPM was expanded to include He^+. This extension was motivated by the Arecibo incoherent scatter radar measurements that indicate He^+ can be the dominant ion at certain altitudes and times. Consequently, the He^+ continuity and momentum equations are now solved simultaneously with the O^+ and H^+ equations along the dipolar geomagnetic field lines. Figure 1 shows sample results from the expanded IPM. The figure shows snapshots of O^+, H^+, He^+ density profiles along dipolar magnetic field lines with apex altitudes of 1000 km (bottom panel) and 5000 km (top panel). The snapshots are for 2400 local time, 293° east longitude, winter (day 335), low magnetic activity (Ap = 4) and medium solar activity ($F_{10.7}$ = 150) conditions. Currently, the expanded IPM is being tested for a wide range of solar cycle, seasonal, and geomagnetic activity levels as well as for several longitudes.

We continued our participation in CIC Caribbean campaigns because of the multi-instrument data that are obtained during these campaigns. Previously, we developed both local and regional data assimilation models for the mid-low latitude ionosphere, and the CIC data are invaluable for testing these models in an environment where multiple data types exist. Currently, we are using GPS-TEC measurements, RAMEY ionosonde data, and Arecibo incoherent scatter radar data. Some of our work is being done in close collaboration with M. Kelley and J. Makela of Cornell University, and S. Gonzalez and N. Aponte of the Arecibo Observatory. During the past year, our mid-latitude data assimilation models were used in several studies involving testing and validation, and these studies are listed in the Publications section. Most of these studies were connected with the CIC Caribbean campaigns that took place during November 1997 and September 1999. However, we also initiated a collaborative effort with Drs. Stephen Thonnard and Sara McDonald at the Naval Research Laboratory

in order to extend our data assimilation work to equatorial latitudes. The effort involved a comparison of electron densities inferred from the UV emission data obtained from the LORAAS instrument on the ARGOS satellite with those calculated with the Ionospheric Forecast Model (IFM), which is an element of AIM. Highlights of this latter work are given in the Results section.

RESULTS

The LORAAS instrument observes line-of-sight ultraviolet limb intensities from naturally occurring ionosphere and thermosphere (IT) airglow emissions. These emissions provide information to infer IT composition and density for day and night. This study used tomographically reconstructed electron density profiles from the nightside emissions. The ionospheric reconstruction was performed using a two-dimensional O^+ 1356Å radiative recombination forward model and discrete inverse theory to determine the best fit for the observations. The forward model assumed a Chapman layer for the vertical electron density distribution from which h_mF_2, N_mF_2, and topside scale height were derived for every 90-second limb scan, approximately 5 degrees in latitude. The results of the inversion process were used to reconstruct nighttime electron density profiles (EDPs). Since ARGOS is in a sun-synchronous orbit, these EDPs form a latitude slice through the equatorial anomaly structures at a single local time. These latitude slices contain information about the north and south anomaly peak densities, heights, and latitudes. Furthermore, from a whole day of these LORAAS observations, the diurnal (longitude) dependence is obtained.

Given that the satellite is in nearly one local time plane and that the anomaly feature develops over many hours in local time, the LORAAS observations are the result of many hours of ionospheric evolution. In order to use these data as a monitor of ongoing ionospheric processes and not just an instantaneous snapshot, it is necessary to assimilate these data into a model that contains an appropriate ionospheric evolution. As a first step toward data assimilation, we compared the ionospheric evolution obtained from the ionospheric forecast model with that obtained from the LORAAS inferred EDPs in order to determine if the two results are physically reasonable and consistent with each other (Sojka et al., 2002). The comparisons were done both as a function of geographic latitude and altitude at a specific UT (longitude) and as a function of geographic latitude and UT.

The period for this comparison was the entire month of October 2000. During the month, there were four days whose average three-hourly Kp index was four or larger. These were removed from the datasets presented as average October 2000 observations because they are noticeably disturbed. The remaining 27 days had an average three-hourly Kp of 2.0. The LORAAS data consisted of 15 orbits per day in the 0230LT sector. In order to produce monthly averages of the EDPs, these orbits were binned into 15 geographic longitude bins each 24° wide. These longitude sectors were further binned into 5° wide geographic latitude bins. In altitude, the EDPs had a resolution of 9 km.

The IFM output was rebinned to provide densities on a similar spatial resolution. A longitude bin was selected from 48, 7.5° geographic longitude resolution slices, and each of these IFM slices had a 3° geographic latitude resolution. In altitude, the IFM profiles were stored at variable resolution. For specific EDP comparisons, the IFM profiles were interpolated on a logarithmic density scale to 5-km steps to be more comparable with the LORAAS EDPs.

Figure 2a shows the LORAAS 27-day average distribution of the equatorial anomaly at 1830UT as contours of electron density. In this figure, both anomalies can be identified. The southern anomaly has a peak density of 7.5 x 10^5 cm^{-3}, at an altitude of 320 km and a geographic latitude of -5°. Its northern anomaly has a density of 8.5 x 10^5 cm^{-3}, but is considerably lower at 230 km and a geographic latitude of 22°. From this set of EDPs, the unexpected difference of 90 km in north-south peak height difference is noted. Physically, such a difference would be associated with a meridional northward wind across the equator. Note the data presented in Figure 2a is the average of 27 days in October 2000 without any smoothing.

Figure 2b is the IFM slice at 1830UT that corresponds to the Figure 2a ARGOS satellite pass. The ionospheric-thermospheric conditions corresponded to an F10.7 solar radio flux index of 171, a mean $F_{10.7}$ of 149, and a daily Ap of 2. In this simulation, the equatorial vertical drift model of Scherliess and Fejer [1999] has been used. The IFM simulation results show two well-defined anomaly peaks. The southern anomaly has a peak density of 7.5 x 10^5 cm^{-3}, a height of 305 km, and is located at -7° geographic latitude, while the northern peak has a density of 9 x 10^5 cm^{-3}, a height of 290 km and is at a geographic latitude of 20°.

The comparison of these two figures is twofold. There are very strong similarities but also a large difference. Namely, the densities and locations are very good and within the latitude resolution. However, the northern anomaly height difference is inescapable. The observations show the F-layer crossing the equator from south to north gradually dropping in altitude from 320 to 230 km. In contrast, the IFM simulation only has a drop in altitude from 305 to 290 km. This overall level of agreement/discrepancy is present in the other 14 longitude (UT) slices. It is also representative of the individual daily slices, excluding the four disturbed days during October 2000. In addition to the northern anomaly height difference, the bottomside density decreases are noticeably different. IFM has a very rapid bottomside decrease, while the LORAAS EDPs fall off more gently.

From the perspective of the ionospheric physics, a north-south equatorial anomaly peak height difference is predominantly caused by a cross equator neutral wind. Both the model and observations indicate, to different degrees, a higher south and lower north height. This would imply a northward neutral wind. Additional follow-on IFM simulations were carried out to test how much asymmetry in height can be achieved by only changing the northward neutral wind. The default IFM uses an HWM [Hedin et al., 1991] to represent this wind. In the midnight sector, this northward wind is very small, less than 10 m/s, but it is northward. Its magnitude is consistent with the small height difference of the IFM anomaly peaks shown in Figure 2b. Because the empirical wind model developed by Hedin et al. (1991) may not be accurate, we conducted several additional ionospheric simulations using different north-south winds. By using a strong northward wind that persisted throughout the night, it was almost possible to model the north-south h_mF_2 differences seen in the LORAAS data. However, the corresponding N_mF_2 values were then significantly different from the measurements. The conclusion is that the preliminary EDPs obtained from the LORAAS data are not consistent with our current understanding of equatorial ionospheric physics. This conclusion initiated a review of the data analysis, and subsequently, a small LORAAS pointing error was detected that needed to be accounted for.

IMPACT/APPLICATIONS

When completed, AIM will provide reliable ionospheric specifications and forecasts on a global, regional, or local grid system. The resulting ionospheric density distributions can then be used for a wide range of applications, including HF communications and geolocations, over-the-horizon (OTH) radars, surveying and navigation systems that use GPS data, and surveillance. AIM has already been used in an ionospheric application connected with data obtained from the ARGOS satellite. The LORAAS UV measurements are a critical data source for data assimilation models like AIM and they provide a development data stream for the future DMSP SSUSI and SSULI operational sensors. In a recent joint effort with scientists from the National Research Laboratory, we compared nighttime F-region electron densities calculated by AIM with those inferred from LORAAS and this comparison provided strong evidence that there was a problem with the data. A subsequent review of the data analysis indicated that there was a small instrument pointing error that had to be accounted for in the data interpretation.

TRANSITIONS

AIM results are being used as part of the Combined Ionospheric Campaign that is under the direction of Stefan Thonnard. As part of the CIC effort, we are conducting AIM simulations in support of the Arecibo ISR measurements being analyzed by Makela and Kelley at Cornell University. The most recent version of the single-station assimilation model (AIM1.06) that was used by Sojka et al. (2002) for the September 1999 CIC Caribbean analysis has been transitioned for use in a related project at SEC. The related project is an SBIR Phase 1 effort to develop software that will use AF DISS data (ionograms) and produce improved bottomside ionospheric parameters as well as the magnetospheric, thermospheric, and solar drivers of the ionosphere. The SBIR effort involves an upgrade of AIM1.06 to provide expanded capabilities. This new version will also be available for the AIM project.

RELATED PROJECTS

This project is related to a project at Utah State University titled 'Global Assimilation of Ionospheric Measurements (GAIM).' The USU project focuses on Kalman filter data assimilation techniques, as applied to both the ionosphere and upper atmosphere. The gridded ionospheric model structure and the mid-latitude assimilation model (AIM-L) developed as part of this AIM project have been delivered to USU to spearhead the USU GAIM initiative. Data sets that we collected under AIM have also been delivered to the USU GAIM program.

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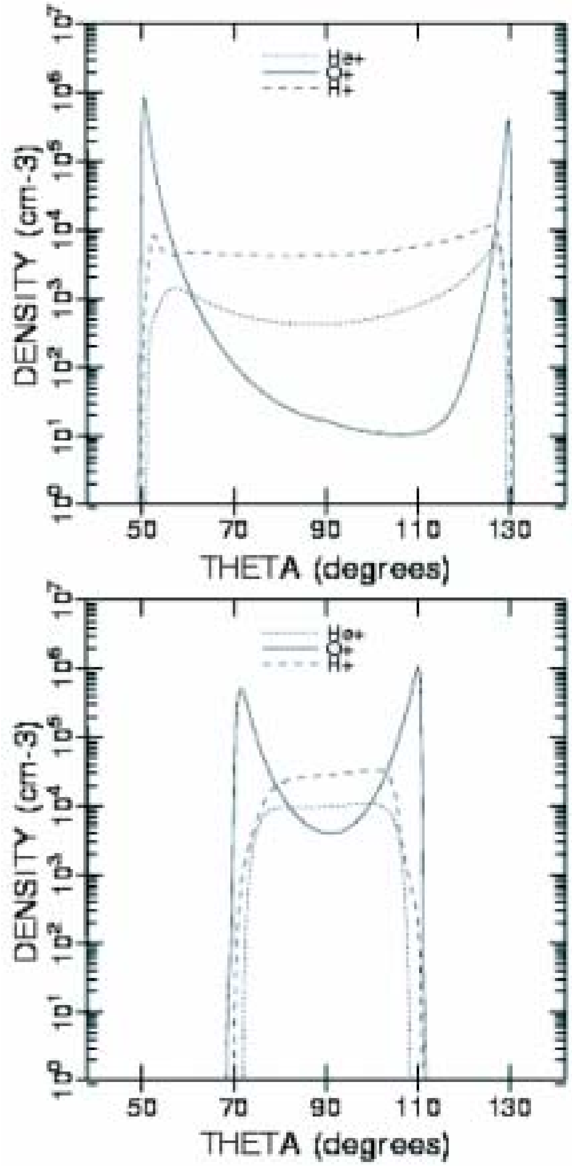

Figure 1. Snapshots of the ion density profiles along dipolar magnetic field lines at 24 local time. The apex altitudes are 1000 km (bottom) and 5000 km (top).

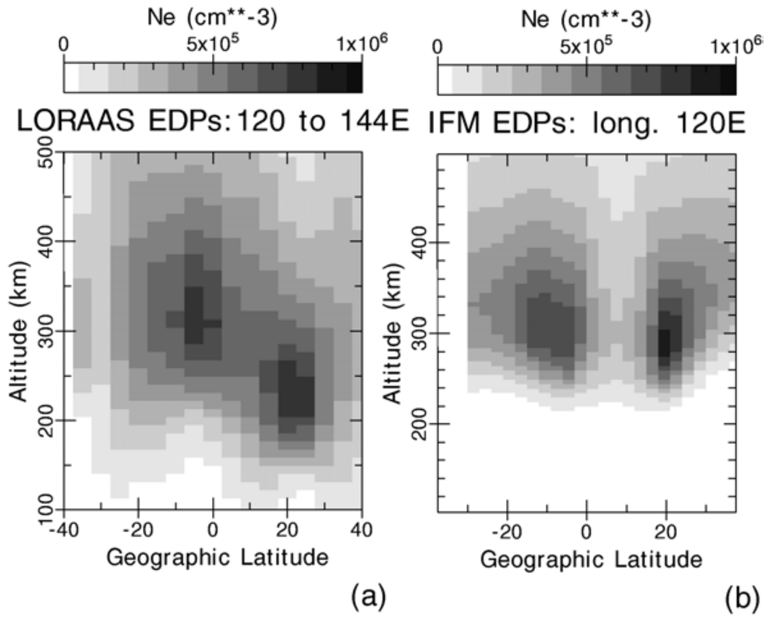

Figure 2. Electron density at 17.7 UT (120° to 144° East) based upon LORAAS UV observations (Panel a) and from IFM (Panel b). From Sojka et al (2002).